Shell-Model Structure of ^{48}Ti Studied via the (d, t) and (α, α') Reactions

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Measurements of the ^{49}Ti(d, t) ^{48}Ti reaction have been carried out at 18 MeV with an energy resolution of about 10 keV. Single-particle strength distributions for $l=0$, 2, and 3 have been obtained up to excitation energy of 7 MeV in ^{48}Ti. About 85% of the $l=3$ strength is found in states below 3.6 MeV, and the total $l=3$ strength is consistent with the sum rule limit for $1f_{7/2}$ transfer to $T=2$ states. About three quarters of the sum rule limit for the $l=2$ strength (assumed be $1d_{3/2}$) and half the limit for the $l=0$, $2s_{1/2}$ strength is observed, with lower limits for the centroid energies of 5.36 and 5.17 MeV for the $1d_{3/2}$ and $2s_{1/2}$ hole, respectively. Measurements of inelastic α scattering on ^{48}Ti have also been carried out at an incident energy of 28.5 MeV with a resolution of 18 keV. These measurements provide many new spin-parity assignments for natural parity states in ^{48}Ti. In combination with the pickup measurements, they provide identification for the centroids of the $J^\pi = (2,3,4,5)^-$ states of the $(f_{7/2}{}^9 \times d_{3/2}{}^{-1})$ multiplet.

I. INTRODUCTION

The structure of ^{48}Ti at low excitations has been investigated by neutron stripping and pickup reactions,[1-8] two-particle stripping and pickup,[9-11] and inelastic scattering of protons,[12-16] deuterons,[17-19] and α particles.[16-23] In addition, precise excitation energies and some spin-parity assignments have been made via $(p,p'\gamma)$, $(n,n'\gamma)$, and (n,γ) measurements.[24-29] A compilation of these results, except for those of Ref. 16, has been published by Rapaport.[30] One more recent (n,γ) measurement[31] extends earlier results to higher excitations and provides spin and parity assignments for a few more levels.

The original motivation for the present pickup measurements was to study the negative-parity states $J^\pi = (2, 3, 4, 5)^-$ arising from the coupling of a $1d_{3/2}$ hole to $1f_{7/2}$ particles in the ^{49}Ti ground state. In addition to the strength distributions for $l=2$ (assumed to be $1d_{3/2}$), distributions were obtained for $l=0$ ($2s_{1/2}$), and $l=3$ (assumed to be $1f_{7/2}$) up to an excitation energy of 7.1 MeV. Since most of the levels above about 4 MeV excitation do not have spin-parity assignments, inelastic α-scattering angular distributions were measured to identify natural-parity states.

II. EXPERIMENTAL TECHNIQUES

The experiments were performed at the University of Rochester's Nuclear Structure Research Laboratory using the tandem Van de Graaff accelerator. The reaction particles were momentum-analyzed in the split-pole magnetic spectrograph and detected in emulsion plates placed in the focal plane of this magnet. Most experimental details were identical to those used in the study of ^{42}Ca described in a previous paper.[32]

Line targets 1 mm in width and about 90 μg/cm^2 in thickness of ^{49}Ti were made by evaporating enriched TiO_2 (76.14% ^{49}Ti) on 20-μg/cm^2 carbon foils, using an electron-gun evaporator. With an incident deuteron energy of 18.0 MeV the over-all energy resolution obtained was 9–10 keV [full width at half maximum (FWHM)]. Measurements

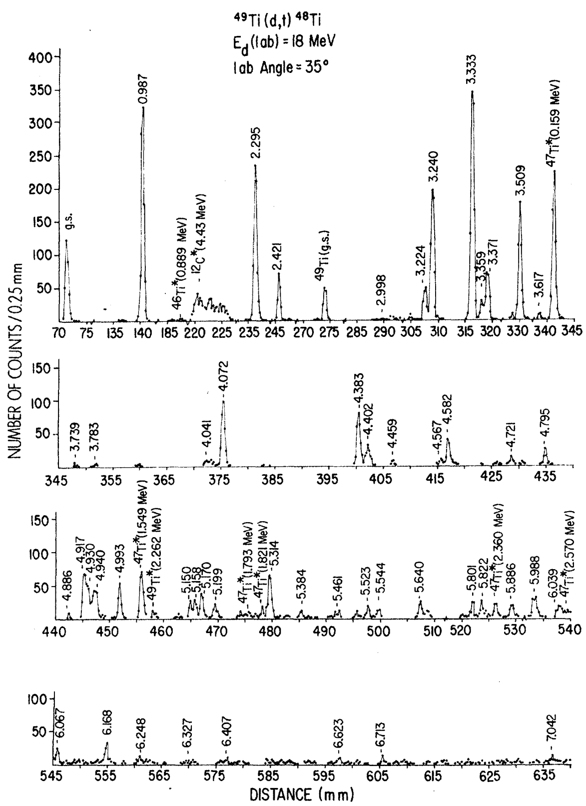

FIG. 1. Triton spectrum from the ^{49}Ti(d, t)^{48}Ti reaction.

were carried out for the angular range 7.5–45° in 2.5 or 5° intervals.

The ^{48}Ti(α, α')^{48}Ti reaction was studied with 28.5-MeV incident α particles. The ^{48}Ti targets of about 50-μg/cm^2 thickness were made by reducing the isotopically enriched titanium oxide (99.13% ^{48}Ti) in a tantalum boat and evaporating the ^{48}Ti on 20-μg/cm^2 carbon foils. Measurements were made at laboratory angles of 13–45° and with angle steps of 2 or 3° at forward and 5° at backward angles. The observed energy resolution was about 18 keV (FWHM).

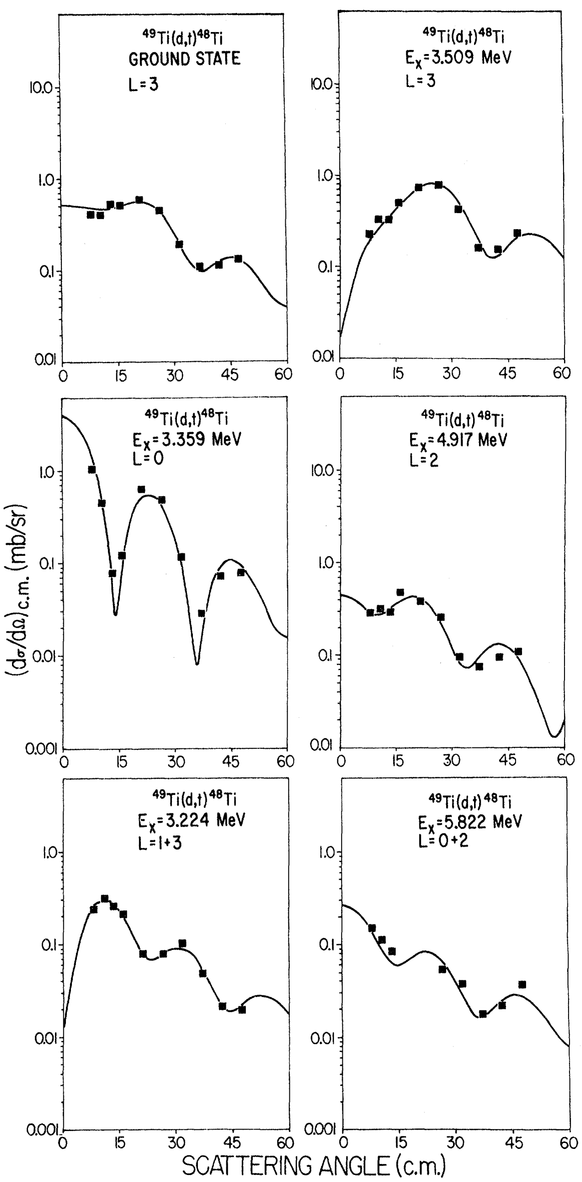

FIG. 2. Triton angular distributions observed in the ^{49}Ti(d, t)^{48}Ti reaction. The solid lines represent DW fits to the data.

III. EXPERIMENTAL RESULTS AND DISTORTED-WAVE BORN-APPROXIMATION ANALYSIS

A typical spectrum of tritons from the ^{49}Ti(d, t)-^{48}Ti reaction is shown in Fig. 1. Groups arising from the ^{48}Ti and ^{50}Ti impurity in the target were readily identified. Typical angular distributions are shown in Fig. 2 for some of the strong groups.

The distorted-wave (DW) analysis of the measured angular distributions was carried out as described in a previous paper.[32] DW calculations using the same optical parameters and lower cutoff radius as for ^{43}Ca(d, t)^{42}Ca were found to give excellent fits for transitions which involved a single l value. For transitions involving a mixture of l values, a least-squares program was used to obtain the best fit for assumed mixture of two l values. Typical fits are shown by the solid curves in Fig. 2.

Transfer l values and spectroscopic factors are listed in Table I for the states observed in these measurements. The table also lists states identi-

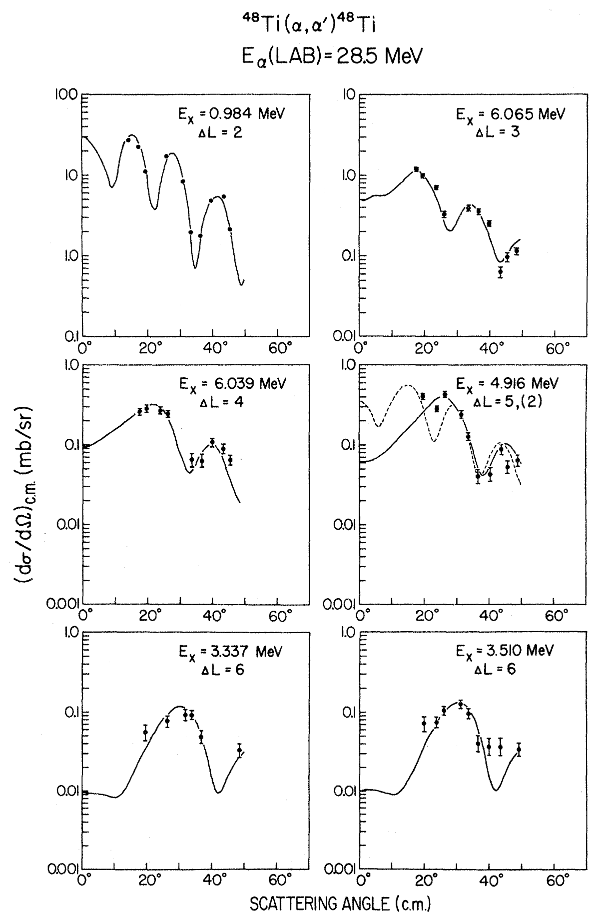

FIG. 3. Typical angular distributions observed in the ^{48}Ti(α,α')^{48}Ti reaction. The solid curves represent DW fits to the data.

TABLE I. Summary of the present and previous results for levels in ^{48}Ti. NS denotes nonstripping, no unique l.

Present results $^{49}Ti(d,t)^{48}Ti$						$^{48}Ti(\alpha,\alpha')$		Previous results $^{47}Ti(d,p)^{48}Ti$ [a]			Other work [b]		
E_x (MeV)	l_1+l_2 [c]	$S(l_1)$	$\Delta S(l_1)$ [d]	$S(l_2)$	$\Delta S(l_2)$	E_x (MeV)	ΔL	E_x (MeV)	Strength $l=1$	Strength $l=3$	E_x (MeV)	J^π	Final J^π
g.s.	3			0.28	±0.01			g.s.	NS		g.s.	0^+	0^+
0.987	3			1.11	±0.05	0.984	2	0.983		1.20	0.9834	2^+	2^+
2.295	1+3	0.02		0.63	±0.03	2.300	4	2.299		0.33	2.2951	4^+	4^+
2.421	1+3	0.01		0.18	±0.01	2.425	2	2.423	0.13		2.4209	(2^+)	2^+
2.998	3			0.02		3.004	(0)				3.000	0^+	0^+
3.224	1+3	0.02		0.07				3.229	0.27		3.2236	(3)	$(3)^+$
3.240	(1)+3	(0.01)		1.10	±0.04	3.241	4				3.2394	(4^+)	4^+
3.333	3			2.18	±0.05	3.337	6	3.342	0.02	0.58	3.3325	6^+	6^+
3.359	0	0.13	±0.01			3.364 [e]	3^+				3.359	(3^-)	3^-
3.371	(1)+3	(0.01)		0.37	±0.02		2	3.377	0.06	≤0.04	3.376	2^+	2^+
3.509	3			1.05	±0.03	3.510	6	3.520		(0.29)	3.5076	$5^+, 6^+$	6^+
3.617	(1)+3	(0.002)		0.01		3.616	2	3.631	0.10		3.6181 *	2^+	2^+
3.739	3			0.02				3.752	(0.02)	(0.34)	3.750	1^+	1^+
3.783	0	0.01									3.7825 *	4	4^-
3.855	0	0.01				3.852	3						3^-
4.041 [f]	(3)			(0.08)		4.045	2	4.048	0.08		4.0357 *	2^+, (1)	2^+
4.072 [f]	(1), (3)	(0.1)		(0.5)		4.073	2	4.087	0.04		4.086		2^+
4.383	1+3	0.06	±0.01	(0.06)		4.384	4				4.3877 *	4^+	4^+
4.402	(1+3)	(0.01)		(0.08	±0.01)	4.407	(2)	4.403	0.46		4.402		$(2)^+$
4.459	(1+3)	(0.002)		(0.01)				4.470	0.26		4.4576	$(2-4)^+$	$(2-4)^+$
4.567	(2)			(0.05	±0.01)						4.578		$(2-5)^-$
4.582	0	0.22	±0.02			4.581	3				4.5831 *	3^-	3^-
4.721	(1+3)	(0.004)		(0.04	±0.01)	4.722		4.734	0.14		4.7187 *	$(2-4)^+$	$(2-4)^+$
4.795	0	0.15	±0.02			4.792	2	4.809	0.06		4.7935 *	2^+	$(3,4)^-2^+$
4.886	(1+3)	(0.004)		(0.04	±0.01)								
4.917	2			0.74	±0.04	4.916	5	4.929	0.09				5^-
4.930	1+3	0.02		0.08	±0.01								$(2-5)^+$
4.940	1+3	0.03		0.14	±0.01			4.956	0.06				$(2-5)^+$
						4.966	2				4.960	$(2)^+$	2^+
4.993	2			0.34	±0.02	4.995							$(2-5)^-$
5.150	1	0.03				5.146	4				5.1463 *		4^+
5.158	1	0.03						5.167	0.26		5.1588 *	$(1-4)^+$	$(2-4)^+$
5.170	(1)+3	(0.01)		0.23	±0.01						5.184		$(0-7)^+$
5.199	(1)+3	(0.003)		0.03							5.205		$(0-7)^+$

TABLE I (*Continued*)

Present results ^{49}Ti$(d,t)^{48}$Ti E_x (MeV)	l_1+l_2 [c]	$S(l_1)$	$\Delta S(l_1)$ [d]	$S(l_2)$	$\Delta S(l_2)$	^{48}Ti(α,α') E_x (MeV)	ΔL	Previous results ^{47}Ti$(d,p)^{48}$Ti [a] E_x (MeV)	Strength $l=1$	Strength $l=3$	Other work [b] E_x (MeV)	J^π	Final J^π
5.314	2			0.62	±0.04	5.313	(2, 4)	5.319			5.318	$(4)^+$	$(2-5)^- 4^+$
5.384	2			0.07	±0.01	5.383	(3)						$(3)^-$
5.461	1+3	0.01		0.03									$(2-5)^+$
5.523	0	0.08	±0.01			5.516	(3)				5.537	(3^-)	3^-
5.544	2			0.12	±0.01			5.563	NS		5.559		$(2-5)^-$
5.617	0	0.11	±0.01										$(3,4)^-$
						5.614	2						2^+
5.640	0+2	0.02		0.13	±0.02								$(3,4)^-$
						5.760	(3)						(3^-)
5.801	0+2	0.01		0.07	±0.01						5.8037 *		$(3,4)^-$
5.822	0+2	0.03	±0.01	0.16	±0.02	5.822	3				5.83	(3^-)	3^-
						5.843	3						3^-
5.886	2			0.13	±0.02								$(2-5)^-$
						5.885	2						2^+
						5.914	2						2^+
5.988	1+3	0.02		0.11	±0.02								$(2-5)^+$
						5.999	(2)	6.008	0.02	≤0.10	6.008		$(2)^+$
6.039	1+3	0.02		0.04		6.039	4				6.0436 *		4^+
6.067	2			0.34	±0.03	6.065	3						3^-
						6.115	2				6.1177 *		2^+
6.168	0	0.27	±0.02										$(3,4)^-$
						6.178	2						2^+
						6.235	3				6.24	$(3^-?)$	3^-
6.248	(1)+3	(0.004)		0.02									$(0-7)^+$
6.327	(0+2)	(0.01)		(0.04)									
						6.342	3				6.36	$(3^-?)$	3^-
6.407	0	0.05	±0.01								6.4064 *		$(3,4)^-$
						6.462	3				6.47	(2^+)	$3^-, (2^+)$
						6.509	4	6.509	0.04	0.42	6.509		4^+
						6.579	(3)						
6.623	(0+2)	(0.01)		(0.05	±0.01)						6.6281 *		
						6.701	4	6.701	0.11	0.46	6.701		4^+
6.713	(3)			(0.11	±0.02)								
						6.740	(2, 3)						

TABLE I (*Continued*)

Present results								Previous results					
$^{49}Ti(d,t)^{48}Ti$						$^{48}Ti(\alpha,\alpha')$		$^{47}Ti(d,p)^{48}Ti$ [a]			Other work [b]		
E_x (MeV)	l_1+l_2 [c]	$S(l_1)$	$\Delta S(l_1)$ [d]	$S(l_2)$	$\Delta S(l_2)$	E_x (MeV)	ΔL	E_x (MeV)	Strength $l=1$	Strength $l=3$	E_x (MeV)	J^π	Final J^π
6.797	(0+2)	(0.01)		(0.06	±0.01)	6.797	(5, 4)						
						6.831	3						3^-
						6.957	3						3^-
7.042	(0+2)	(0.01)		(0.10	±0.02)								
						7.058	(3)						
						7.986	2						2^+

[a] Reference 8. The quoted strengths are given by $[(2J_f+1)/(2J_i+1)]\,C^2S^+$.

[b] References 30 and 31. Energies marked with an asterisk are from Ref. 31.

[c] Values of l in parentheses indicate uncertain fits due to missing experimental points or poor statistics. For mixed transitions, parentheses on one component only indicates that the data permits, but does not require, a small admixture. The corresponding spectroscopic factor represents an upper limit for that component.

[d] The quoted uncertainties in the spectroscopic factors are due to statistical errors only. For weak states for which no error is given, it is generally about 25% of the quoted strength.

[e] Unresolved doublet.

[f] These levels were obscured by elastic deuterons at forward angles. No l assignment was possible; quoted strengths are given on the assumption of unmixed transitions.

fied in other measurements along with existing spin-parity assignments. In general, it has been assumed that the same level is being observed in the (α, α') or (n, γ) measurements as in (d, t) if the energies agree within 5 keV, and the indicated spins and parities are consistent. The suggested correlation between (d,p)[8] and (d, t) measurements is less certain. Above 3 MeV excitation, the energies reported in (d,p) appear to be higher than those in (d, t) by about 12 keV on the average. We have assumed that the same level is excited in both reactions if the reported energy from the (d,p) results is between 7 and 17 keV higher than the present results, and if the spin-parity limitations are consistent in both measurements. If the latter requirement is not met, it has been assumed that different components of an unresolved doublet are excited in different reactions, and the different spin-parity combinations are both listed in the last column.

Angular distributions for typical results of the inelastic α-scattering measurements are shown in Fig. 3. The solid curves show the distorted-wave Born-approximation (DWBA) calculations using the same optical parameters as were used for the ^{42}Ca(α, α') measurements. In general, the resultant fits permit assignment of L transfers and spin-parities for the states excited. These assignments are also summarized in Table I.

IV. DISCUSSION

The results of the present measurements have been summarized and compared with previous results in Table I. The spectroscopic factors reported for the present measurements have assumed $1f_{7/2}$ transfer for $l=3$, $1d_{3/2}$ for $l=2$ and $2s_{1/2}$ for $l=0$. The neglect of $1f_{5/2}$ transfer has some justification in the observation that the strength of $l=1$ transfers indicates little p-state excitation in the ^{49}Ti ground state. The total $l=1$ strength shown in Table II indicates an occupation probability of 6% for the $2p$ neutron orbits, and the $1f_{5/2}$ excitations would be expected to be of comparable magnitude. The $1d_{5/2}$ strength is expected to be important at energies several MeV higher than the $1d_{3/2}$ strength which appears to be concentrated in the energy range from 4.9 to 6.1 MeV. It is thus expected that most of the $1d_{5/2}$ strength would be at higher excitation energies than have been studied here, though small contributions are probably present in some of the observed $l=2$ transitions.

TABLE II. The observed and expected total pickup strengths for the $T_<=2$ states in ^{48}Ti. Strength $G_{l_<}=\sum C^2S_l$.

	Spectroscopic strength $l=0$	$l=1$	$l=2$ $(d_{3/2})$	$l=3$ $(f_{7/2})$
Observed	1.07	0.32	2.72	7.70
Sum rule	1.66	0.00	3.33	6.66

For all strongly excited levels, the transfer l values involved could be unambiguously identified using a least-squares fitting program. For some of the weaker states identification was less certain, and these are shown in parentheses. In these cases, the value listed gives the best fit to the experimental data, but other possibilites could not be completely excluded. Between 4 and 5 MeV excitation, elastically scattered deuterons produced a background which interfered with the identification of triton groups at some angles. Most of the uncertain l assignments fall in this region, and generally are the result of missing points in the angular distributions.

The total $l=3$ strength observed in these measurements is about 20% greater than the sum rule limit for $1f_{7/2}$ pickup to $T_<=2$ states, assuming a ground-state configuration of $(f_{7/2})^9$ for ^{49}Ti. This is quite satisfactory considering the fact that the optical parameters are taken from the analysis of the ^{43}Ca$(d, t)^{42}$Ca results without further adjustment or renormalization. The distribution of $l=3$ strength for transitions to states up to 3.61 MeV is in good agreement with the results of earlier (p, d) measurements[2] except for a difference of about 25% in over-all strength. In addition, the improved resolution in the present measurements permits the observation of weaker states not observed in (p, d).

A comparison between the present results for $l=3$ pickup and the predictions of a model calculation[33] assuming only $1f_{7/2}$ particles is shown in Fig. 4. It is clear that the model predicts the location and strength very well for many levels below 4 MeV, although the observed strength is too low for the second 2^+ state at 2.421 MeV, and too high for the 6^+ state at 3.333 MeV. It is interesting that the lowest 1^+ state, predicted at 3.83 MeV with a strength $S=0.01$ is observed at 3.739 MeV with $S=0.02$. Another prediction of the model is a 3^+ state at 3.01 MeV. The state observed at 3.224 MeV has recently been tentatively assigned[16] $J^\pi=(3^+)$, and this assignment is supported by the fact that the state is not observed in inelastic α scattering. The observed state is certainly more complex than the model state, however, as it is excited partly by $l=1$ pickup, and is strongly excited by $l=1$ stripping in the ^{47}Ti$(d,p)^{48}$Ti reaction.[8] It is also probable that the strongest $l=3$ transition above 4 MeV (5.170 MeV, $S=0.23$) corresponds to the 6^+ state which is predicted at

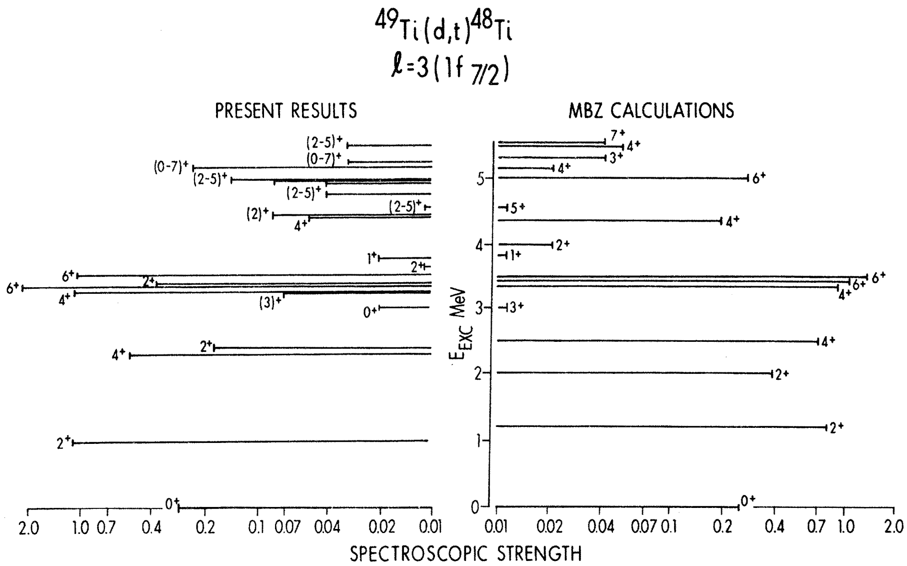

FIG. 4. Comparison of the observed $l=3$ strength with that predicted by the McCullen, Bayman, and Zamick (MBZ) calculation for the ^{49}Ti$(d, t)^{48}$Ti reaction.

4.97 MeV with $S=0.27$.

Further information on the structure of these even parity states is provided by a comparison with results of the ^{47}Ti$(d,p)^{48}$Ti measurement which show relatively strong $l=1$ transitions to the states at 2.421, 2^+; 3.224, $(3)^+$; 3.371, 2^+; and 3.617, 2^+. This result indicates the importance of excitation into the $2p$ orbit even for the low-lying states. At excitations above about 4 MeV, configuration mixing is expected to be important, and this is borne out by the large number of strongly mixed transitions observed in pickup as well as stripping.

Another interesting result in the (d,p) measurements is the observation of stripping transitions with a strong $l=3$ component to states at 5.398, 5.510, 6.509, and 6.701 MeV. These are presumably $1f_{5/2}$ transitions, and the fact that none of these states is excited in the pickup reaction provides additional support for the assumption that $1f_{5/2}$ excitations in the ^{49}Ti target ground state may be neglected.

Among all the low-lying states, the 0^+ state at 3.00 MeV is the only one clearly outside the model space spanned by coupling a hole to the ^{49}Ti ground state (g.s.) or a particle to the ^{47}Ti g.s.

At least 19 negative-parity states formed by coupling a $2s_{1/2}$ or $1d_{(3/2)}$ hole to the ^{49}Ti g.s. have been observed in these measurements. In addition, five weakly excited states are tentatively identified as having negative parity. This total of 24 states is to be compared with the 6 expected on a simple weak-coupling model. Assuming a simple $(1f_{7/2})^9$ configuration for the ^{49}Ti ground state and normalizing the observed total strengths so that the sum rule limit for the $l=3$ $(1f_{7/2})$ transitions is met, then the total $l=2$ strength amounts to about 72% of the sum rule limit for $1d_{3/2}$ pickup, while the total $l=0$ strength is only about 56% of the sum rule limit for $2s_{1/2}$ pickup. It may be reasonable to assume that all $1d_{3/2}$ strength has been observed, within the usual uncertainties of the DWBA, but it appears that a significant fraction of the $2s_{1/2}$ strength has not been observed.

From the (α, α') results it is possible to identify a large number of 3^- states which are generally strongly excited in inelastic scattering, along with one 5^- state at 4.917 MeV. If it is assumed that the negative-parity states not excited in (α, α') have unnatural parity, then it is possible to use the pickup results to place rather narrow limits on the centroids of the $(f_{7/2}{}^9 \times d_{3/2}{}^{-1})$, $J^\pi = (2, 3, 4, 5)^-$ states. Only three states with $J^\pi = 3^-$ are excited by $l=2$ pickup, and the strength in those states is consistent with that expected for the 3^- state of the simple multiplet. The centroid energy of these states is 5.91 MeV. The single 5^- state at 4.917 MeV contains most of the expected 5^- strength. Candidates for assignment as 5^- states must exhibit pure $l=2$ pickup, and hence could be only the states at 4.993, 5.314, 5.544, or 5.886 MeV. The first two states are unlikely to have $J^\pi = 5^-$ since the strength of either of these, taken along with that of the 4.917-MeV state would exceed the expected limit for the 5^- state. Of the remaining two states, the one at 5.544 MeV is definitely not excited in the (α, α') reaction. The state at 5.886 MeV is apparently excited with $\Delta L = 2$, indicating an unresolved doublet near this energy. Both states exhibit the same strength in pickup, which is approximately that needed to satisfy the sum rule limit for 5^-. Thus the 5^- centroid can be located at 5.01 or 5.07 MeV, with the higher energy somewhat more probable. The 2^- states must also be excited by pure $l=2$ pickup, and thus could be states at 4.993, 5.314, and 5.544 or 5.886 MeV. Of these, the 5.314-MeV state carries too much strength to permit the 2^- assignment, while the 4.993-MeV state plus either one of the other two carry about the expected total strength. If the 5.886-MeV state is accepted as 5^-, then the 2^- centroid can be located at 5.15 MeV. The state at 5.314 MeV which shows a strong $l=2$ transition, and is not excited in (α, α') is a good candidate for a $J^\pi = 4^-$ assignment. The strength is about 75% of the sum rule limit for 4^-. The states then remaining as candidates for 4^- assignment are the $l=0+2$ mixed transitions at 5.640, 5.801, 6.327, 6.623, 6.797, and 7.042 MeV. If all these are in fact 4^- states then the measured strength exceeds the 4^- sum rule limit by about 30%. However, for states above 6 MeV of excitation, the cross sections are small and l discrimination rather uncertain. Also the excitation of the $1d_{5/2}$-hole strength may become significant at these energies. The three states at 5.314, 5.640, and 5.801 MeV would approximately satisfy the 4^- sum rule limit, and give a lower limit of 5.40 MeV for the 4^- centroid. If the other states mentioned are included, the centroid would be located at 5.73 MeV. The centroid of the total $l=2$ strength is located at 5.36 MeV.

The $l=0$ strength is seen to be rather more fragmented and spread over a wider energy region than the $l=2$ strength. Since the total $l=0$ strength is appreciably less than the sum rule limit, the present data for the $(f_{7/2}{}^9 \times 2s_{1/2}{}^{-1})$, $J^\pi = 3^-, 4^-$ states may be of questionable validity. As a first approximation however, we may assume that all 3^- states below 7.1 MeV have been identified in the (α, α') reaction, and that all other states showing $l=0$ pickup have $J^\pi = 4^-$. If this is done, it is found that the ratio of total strengths for 3^- and 4^- states is very close to that expected for the pure states. This result may indicate that all the $l=0$ strength has in fact been observed, and that the total strength is being seriously underestimated by the DWBA. Alternatively it may be simply that both the 3^- and 4^- states have the same fraction of their strength in transitions to states above the upper limit of 7.1 MeV excitation observed here. The observed centroids are 4.47 MeV for 3^- and 5.70 MeV for 4^-, with the over-all centroid for the multiplet at 5.17 MeV.

SUMMARY

The observed sum total strengths for the single-neutron pickup from the $l=0, 1, 2,$ and 3 orbitals (assumed to be $2s_{1/2}$, $2p_{3/2}$, $1d_{3/2}$, and $1f_{7/2}$) are listed in Tabel II and compared with the expected sum rule values. The results for $l=3$ pickup transitions below 4 MeV are in generally good agreement with a model calculation, assuming only $1f_{7/2}$ particles. Comparison of the ^{49}Ti(d, t) and ^{47}Ti(d,p) results indicates that the positive-parity states not predicted by this model are mainly due to the $[(1f_{7/2})^7 \times 2p]$ configuration. The observed $2s_{1/2}$ and $1d_{(3/2)}$ pickup strengths are fragmented among about 24 levels, as compared with the 6 expected on a simple weak-coupling model. Within the usual DWBA uncertainties, it can be assumed that all the $1d_{3/2}$ strength has been observed, with the centroid at 5.36 MeV. As a result of the present (α, α') work, spin assignments have been made for many natural-parity states. Based on the (d, t) and (α, α') results, suggestions have been made for spins of some of the states and rather narrow limits are placed on the centroids of the members of the $[(1f_{7/2})^9 \times 1d_{3/2}{}^{-1}]$, $J^\pi = (2, 3, 4, 5)^-$ multiplet. The $2s_{1/2}$ pickup strength is seen to be more fragmented than the $l=2$ strength. Assuming all the $l=0$ states not observed in the (α, α') work are 4^- states, then it is found that the ratio of total strengths for 3^- and 4^- states is very close to the expected value. Lower limits are established for centroids of the $[(1f_{7/2})^9 \times 2s_{1/2}{}^{-1}]$, $J^\pi = (3, 4)^-$ multiplet, but further measurements are needed to determine whether states above 7.1 MeV carry appreciable $l=0$ strength.

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